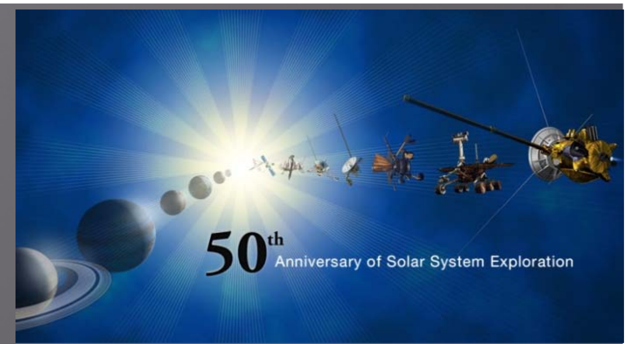


OUTER SOLAR SYSTEM EXPLORATION: AN ARCHETYPE OF THE SCIENTIFIC METHOD

Torrence V. Johnson

Jet Propulsion Laboratory, California Institute of Technology

26 October 2011

Scientists amazed …

Scientists surprised …

Textbooks rewritten!!

Unexpected result stuns scientists!

Well … not quite.

But

“Scientists confirm their model while finding some new puzzles.”

doesn’t make nearly as lively copy.

The Scientific Method

Observations, Hypothesis Development, Prediction, New Observations allowing Hypothesis Testing, Modification of Hypotheses …

Operates in a more deliberate fashion.

Outer Solar System Exploration

- Vast distances and long flight times dictate a careful application of the scientific method.
- Experiments have to be selected years before launch based on best available scientific information - but designed to be flexible enough to be reprogrammed at the target, incorporating new discoveries and theoretical advances.

Illustrate this process for two key scientific questions

- Giant Planet atmospheric composition
- Nature and history of Giant Planet Satellites.

These questions have been major scientific goals of outer solar system exploration and are both tied closely to our evolving understanding of the solar nebula and planetary formation processes.

Outer Solar System Exploration – the beginning

- ca 1970 – less than 10 yrs after Mariner 2 launch
- Grand Tour developed – alignment of JSUN made reconnaissance of outer solar system in a reasonably time feasible
- GT descoped to Pioneer 10/11 to flyby Jupiter with Voyager 1/2 to flyby Jupiter and Saturn with an option for Uranus and Neptune

1970: State of Knowledge Solar Nebula and Giant Planets

- First widely used quantitative solar nebular models developed by Al Cameron (several per year?!)
- Giant planet formation models – massive gravity should result in accretion of solar nebular gas with no fractionation: "a pristine sample of the original material from which the Sun and planets were made."
- H/He in Jupiter becomes "the Holy Grail"

1970: State of Knowledge Giant Planet Satellites

- Basic parameters poorly known: mass, radius, albedo, composition, ephemerides
- General view that the regular satellites should be "cratered ice balls" with some being more rock rich.

Galilean Satellites

1970

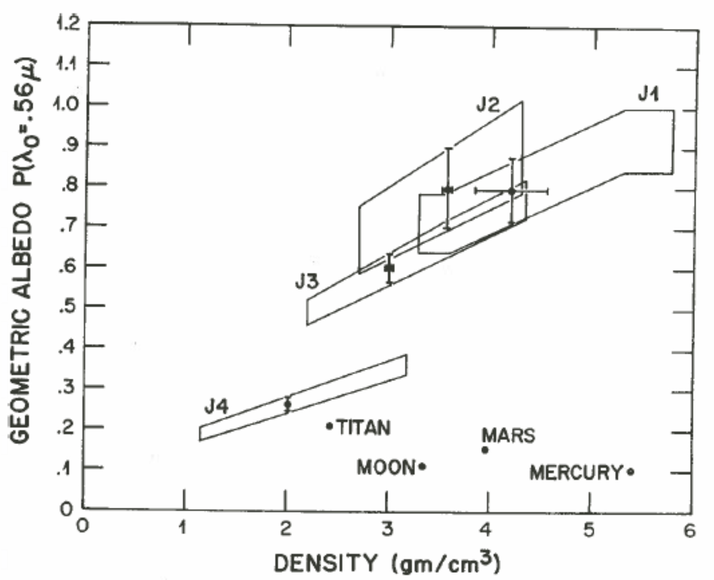


Figure 19. Geometric albedo vs density of the satellites. The point for each satellite represents the values of p and ρ for the mean of the measured diameters. The density error bar gives the limits of two mass determinations (Porter, 1960) and the geometric albedo range is determined from the rotation variation shown by the satellite. The regions indicated for each satellite indicate the limits of the given error bars for the range of diameter measurements compiled by Sharonov (1958).

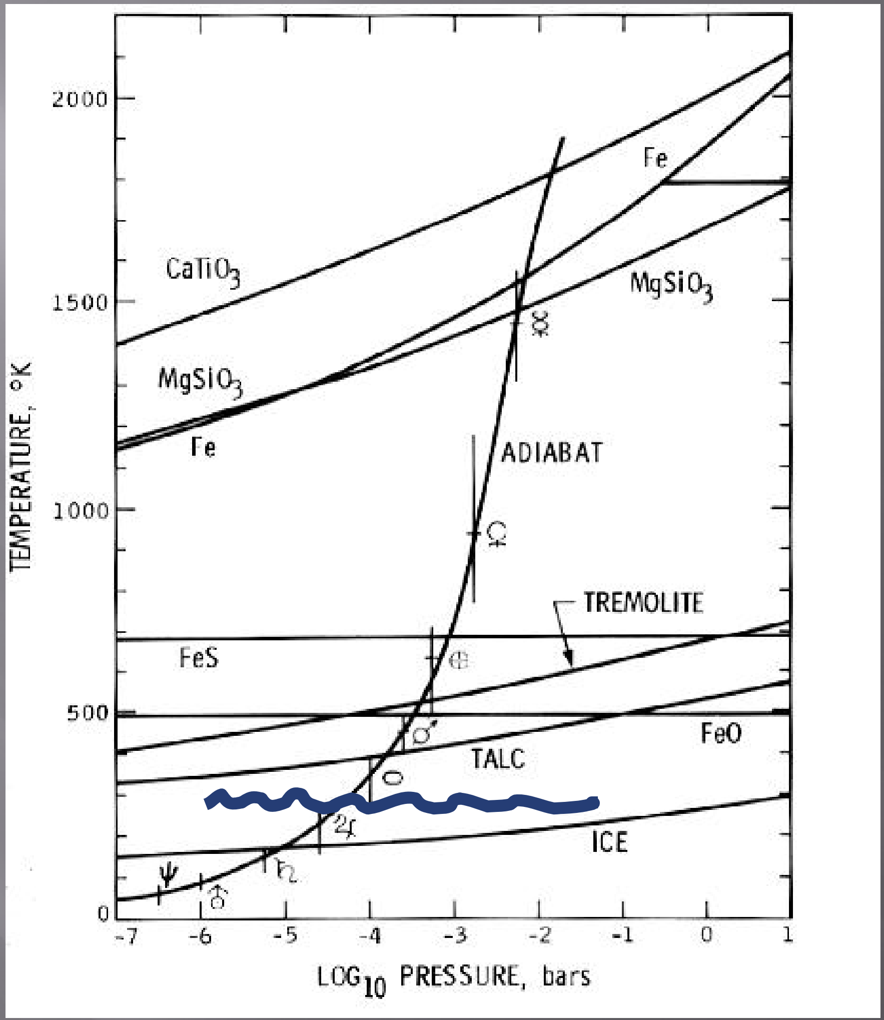
- Voyager originally planned on the basis of an encounter with one (1) 'icy' and one (1) 'rocky' satellite.
- Voyager imaging team had two (2) planetary geologists – presumably one first author per satellite target.

T. V. Johnson, PhD Dissertation, 1970

Preparing for Voyager: Rapidly Evolving Knowledge

- Cameron nebular models applied to satellite compositions – John Lewis, 1971
  => Icy satellites should have ~50/50 ice/rock mass ratios and can be geologically active
- Occultation of star by Ganymede 1972
  - Determined radius accurately
- Pioneer determined mass of Ganymede
  - Density matched Lewis' model
- Sodium cloud discovered around Io
- Water ice identified on Ganymede and Callisto

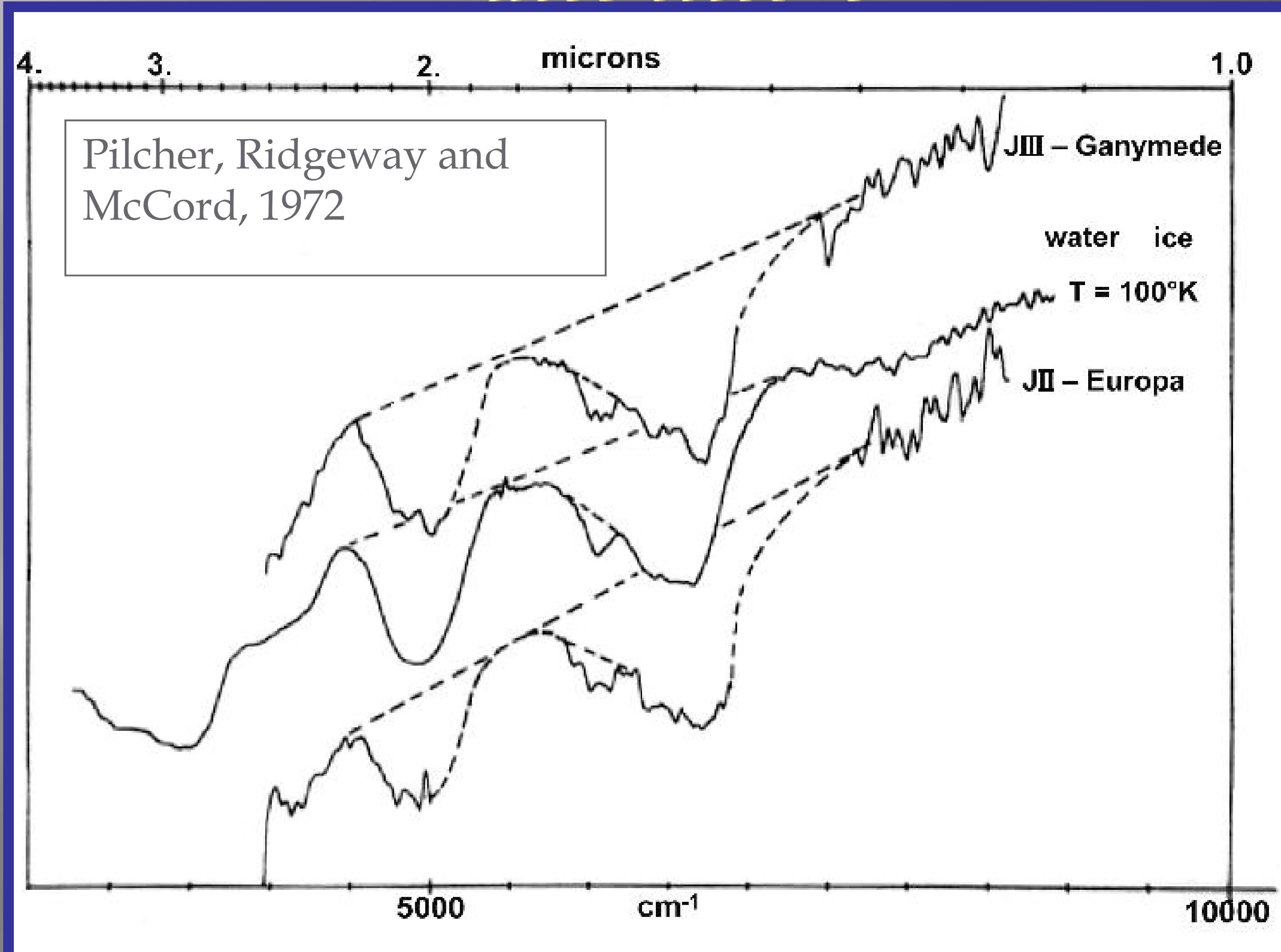
Lewis: Solar Nebula Adiabat



"Water Line" of the Solar System

Ganymede Occultation
Indonesia, 1972

Water Ice Identified on Satellites



OUTER PLANETS SATELLITES

July 9, 1975

T. V. Johnson

COMPLEX Meeting
Seattle, Washington

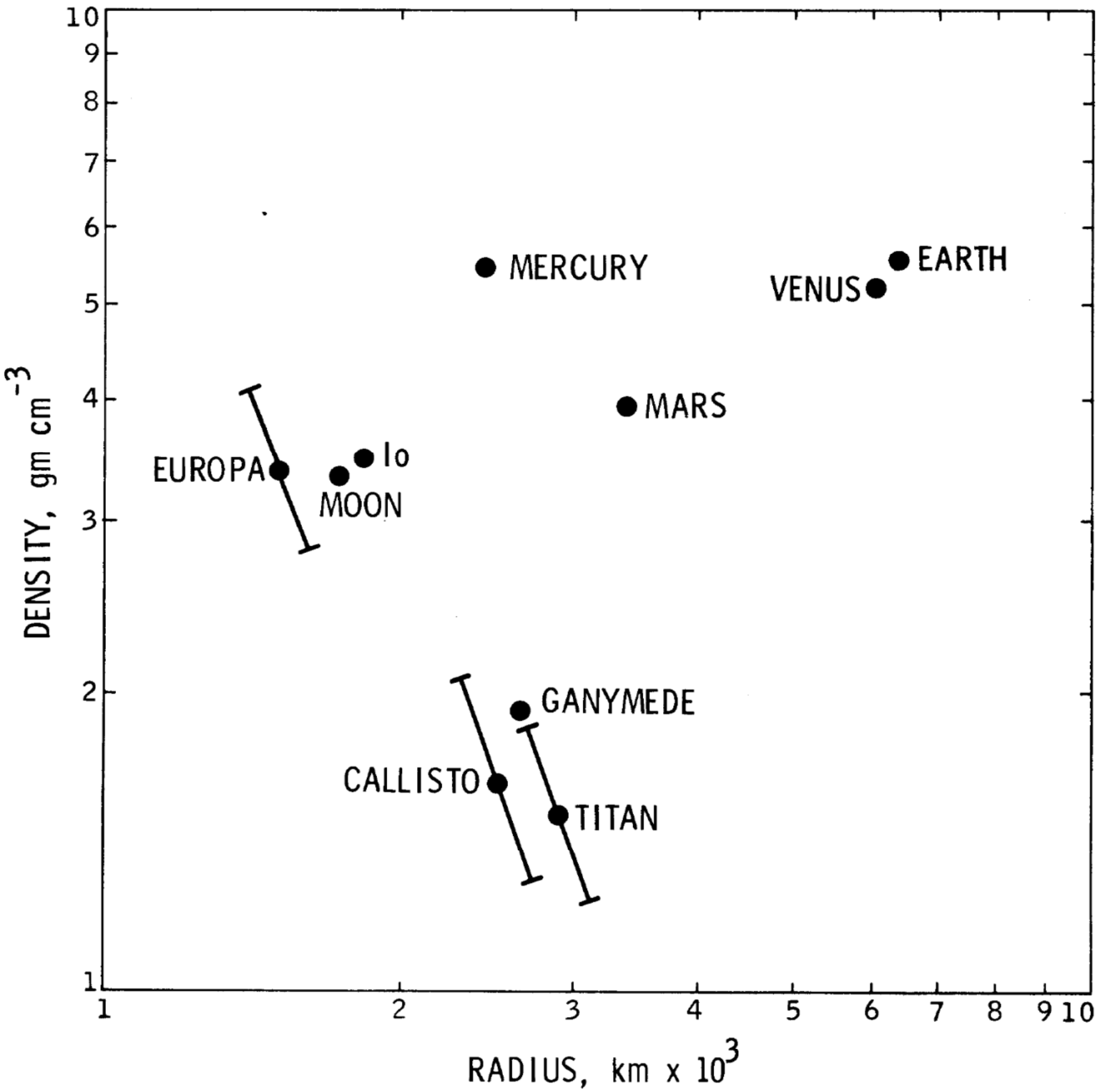
SATELLITES AS PLANETS

- BASIC OBSERVATIONS
  - GANYMEDE AND TITAN (AND PROBABLY CALLISTO) ARE LARGER THAN THE PLANET MERCURY, MANY OTHERS ARE LUNAR-SIZED
  - SATELLITES EXHIBIT A WIDE RANGE OF BULK DENSITIES (AND THEREFORE COMPOSITIONS), RANGING FROM "PURE ROCK" to "PURE ICE"
  - MANY SATELLITES HAVE VARIATIONS IN OPTICAL PROPERTIES (AND HENCE COMPOSITION) ACROSS THEIR SURFACES
- CONSEQUENCES
  - DIFFERENTIATION (ICE/SILICATE) EXPECTED EVEN FOR RELATIVELY SMALL ICY SATELLITES - Lewis

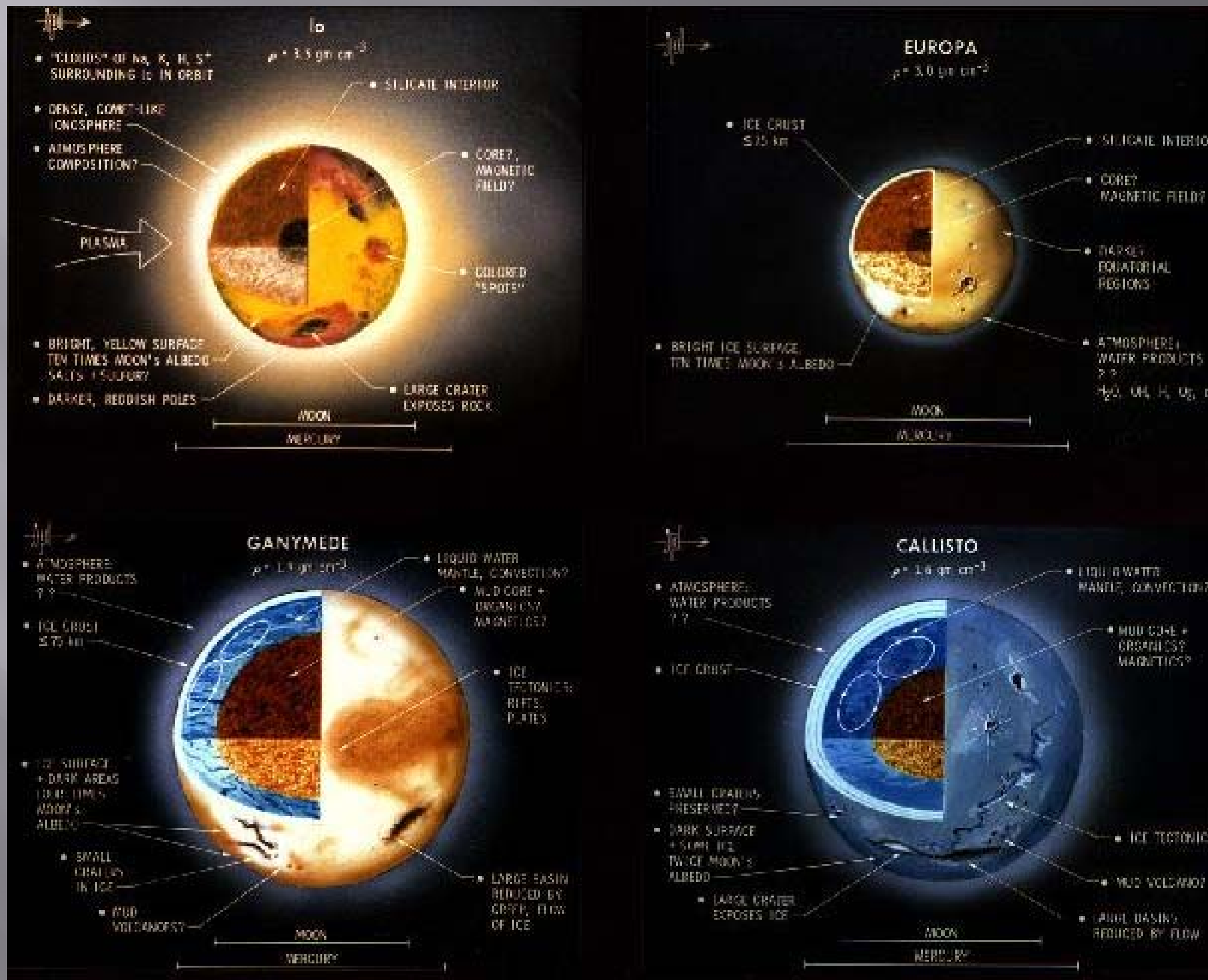
SATELLITES AS PLANETS
(Contd)

- CONSEQUENCES (Condt)
  - NEW GEOLOGIC AND TECTONIC PROCESSES EXPECTED
    - WIDELY DIFFERING DEGASSING HISTORIES
    - ICE CRUSTS, LIQUID MANTLES, "MUD" CORES
    - IMPACT FEATURES IN ICE OR ICE/ROCK SURFACES
    - CREEP DEFORMATION MAY DOMINATE TOPOGRAPHIC REDUCTION
    - POSSIBLE PLATE TECTONIC-TYPE ACTIVITY: FISSURES, RIFTS

TERRESTRIAL PLANETS-SATELLITES COMPARISON



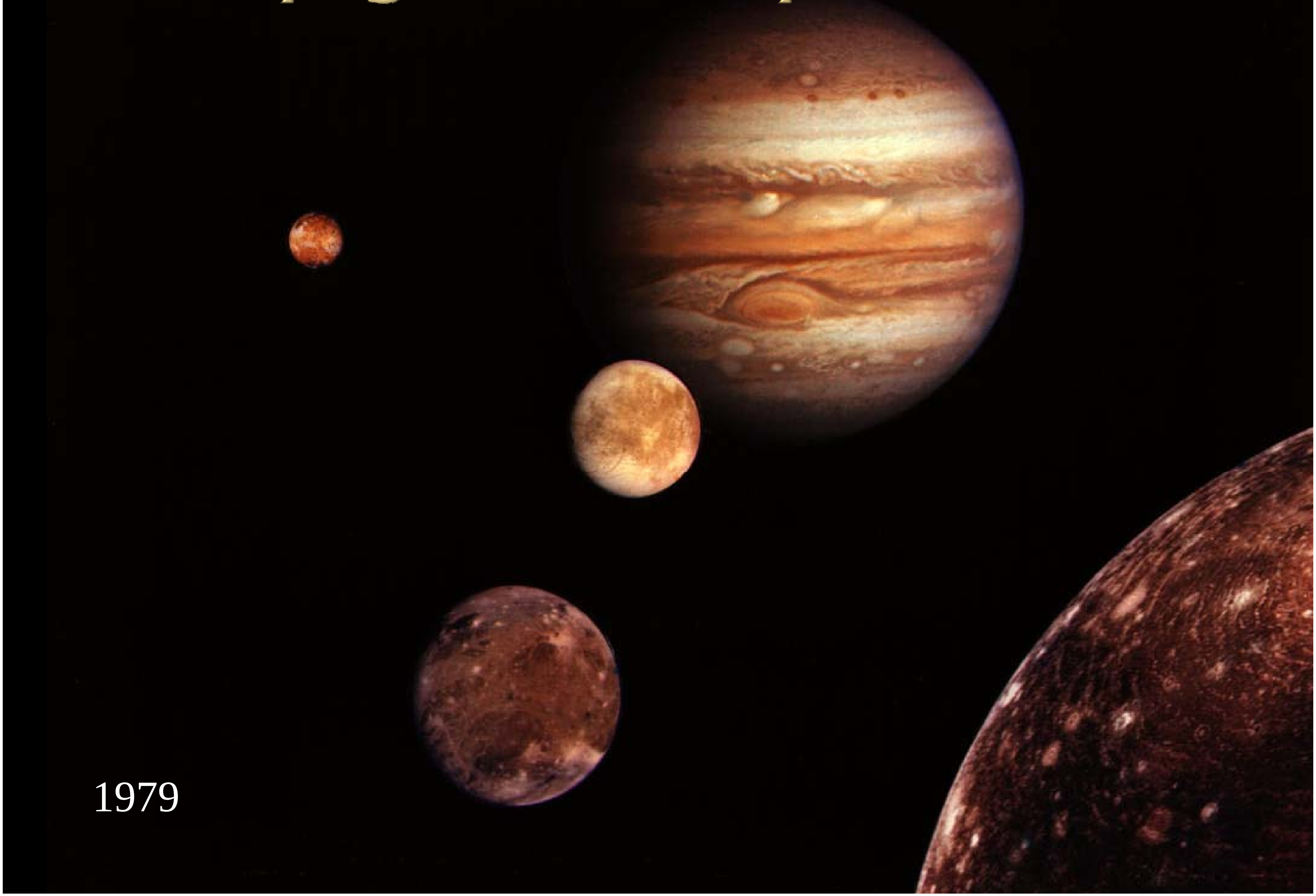
Satellite Models: 1977



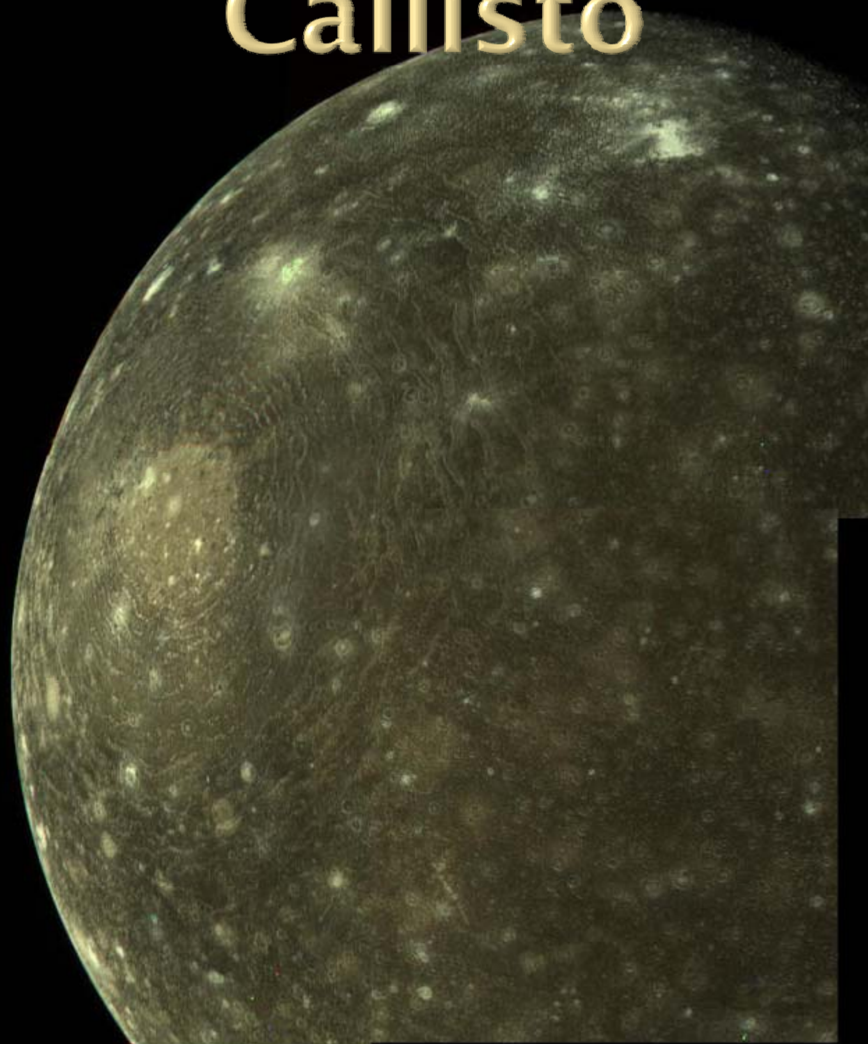
Voyager Plans Modified

- Instruments selected in 1972 – no change
- Multiple satellite flyby opportunities included in mission plan
- More satellite scientists included in teams

Voyager: "Family Portrait"



Callisto



1979 - Voyager

Ganymede

1979 - Voyager

Europa

1979 - Voyager

Io's Volcanoes: Discovery Picture

1979 - Voyager 1

Preparing for JOP (Galileo): Major Advances over Voyager

- 1976 – over a year before Voyager launches! Science Working Group headed by James Van Allen recommended a combined Orbiter and Probe mission to Jupiter to address post Voyager science goals in COMPLEX reports.
- Key elements of science:
  - H/He – Pioneer and Voyager unable to provide required accuracies, other key atmospheric components poorly defined. => atmospheric Probe (major goal of 2 Probe measurements)
  - Increased emphasis on satellites and interaction with magnetosphere => satellite surface composition experiments and sophisticated space physics package

660-26

A Science Rationale For Jupiter Orbiter Probe 1981/1982 Mission

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

Ames Research Center
Moffett Field, California 94035

August 1976

National Aeronautics and Space Administration

PREFACE

The Jupiter Orbiter with Probe Science Working Group (JOPSWG) was formed in January 1976. The objectives of the group were to assess the science priorities for Jupiter exploration as developed by the Committee on Planetary and Lunar Exploration (COMPLEX), to recommend a typical payload for both Orbiter and Probe, and to recommend a mission and spacecraft concept which would be consistent with fiscal constraints. The group was asked to develop a mission which would be exciting and saleable as well as one which would be scientifically sound.

This science rationale is presented as background material for proposers. The JOPSWG also transmitted to NASA a specific set of recommendations and conclusions as part of its final report. The members of the JOPSWG are given below:

Member	Affiliation
Dr. James A. Van Allen (Chairman)	University of Iowa
Dr. Donald M. Hunten (Vice-Chairman)	Kitt Peak National Observatory
Dr. James R. Arnold	Revelle College
Dr. Ian Axford	Max Planck Institute, Federal Republic of Germany
Dr. Michael J. S. Belton	Kitt Peak National Observatory
Dr. Lawrence Colin	NASA/Ames Research Center
Dr. Samuel Gulkis	Jet Propulsion Laboratory
Dr. William B. Hubbard	University of Arizona
Dr. Torrence V. Johnson	Jet Propulsion Laboratory
Dr. Charles F. Kennel	University of California at Los Angeles
Dr. Konrad Mauersberger	University of Minnesota
Dr. Norman F. Ness	NASA/Goddard Space Flight Center
Dr. James B. Pollack	NASA/Ames Research Center
Dr. U. von Zahn	Physikalisches Institut der Universitat Boon, Federal Republic of Germany
Dr. James W. Warwick	University of Colorado
Dr. John H. Wolfe	NASA/Ames Research Center

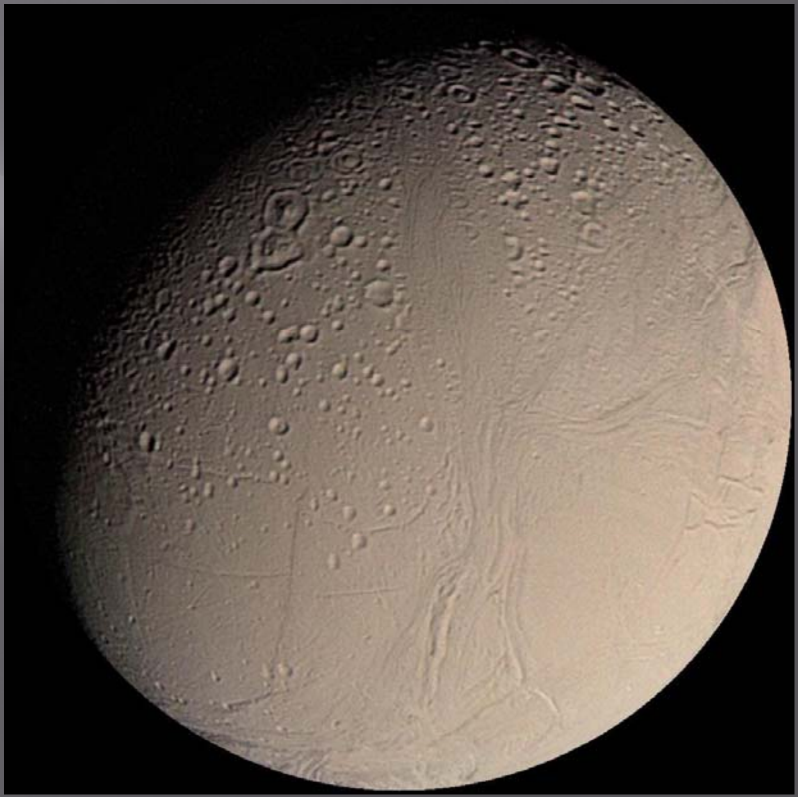
Preparing for JOP (Galileo): Response to Surprises

- FY '77 – JOI AO and experiment selection
- 1979 – Voyager 1/2 flybys of Jupiter 'surprises'
  - Active volcanism on Io (volcanism NOT a surprise (Peale et al, 1979), surprise was that tidal heating of satellites had been hiding in plain sight for so long)
    Magnitude of tidal heating still not completely explained
  - Europa's youthful surface – combined with possibility of tidal heat => liquid ocean models
- Modified mission plan to increase number of satellite encounters from 3 to 12, and include Europa in spite of increased radiation.

Voyager at Saturn 1981
What it didn't see.

THE SURFACE OF TITAN

LOTS OF CRATERS ON ENCELADUS



Preparing for Cassini

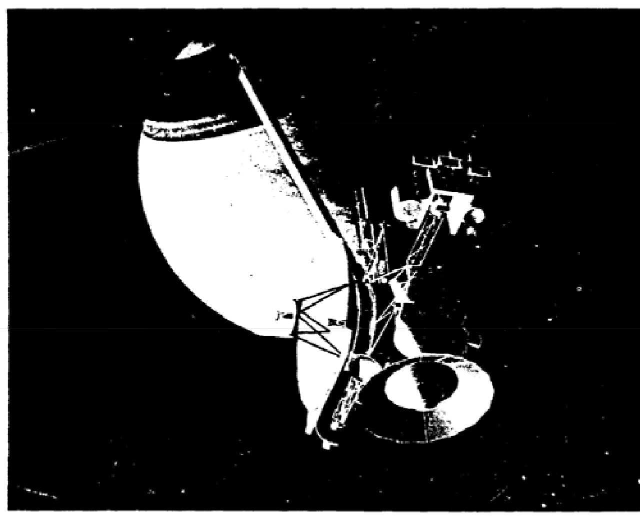
- Planning for Cassini began jointly with ESA ~ 1984, 3 years after Voyager Saturn encounter and 5 years before Galileo launch.
- Original study missions were for "Super Galileo's" with an Orbiter and both Saturn and Titan Probes
- Descope - Titan Probe (Huygens) chosen based on Voyager results and technical difficulty of deep (>100 bar) probe at Saturn.
- Titan and Enceladus went to top of satellite priority list
- Radar, IR spectrometer and Imaging system optimized to "see through" Titan's clouds.

esa NASA

CASSINI

SATURN ORBITER AND TITAN PROBE

ESA/NASA ASSESSMENT STUDY

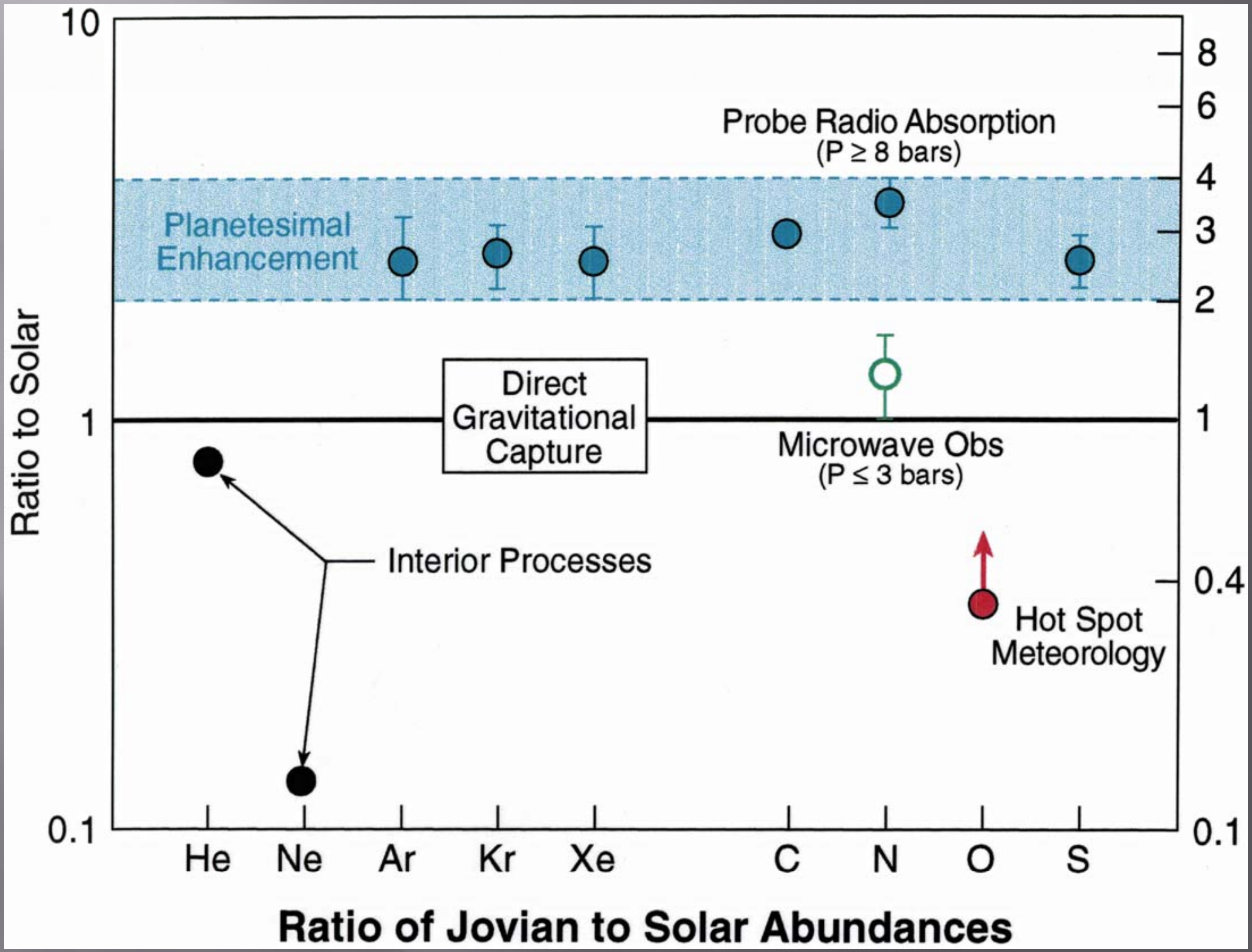


AUGUST 1985

ESA REF: SCI(85)1

GALILEO LAUNCH OCT. 1989
JUPITER ARRIVAL DEC. 1995

1995: Galileo Probe Data
Atmosphere NOT solar composition

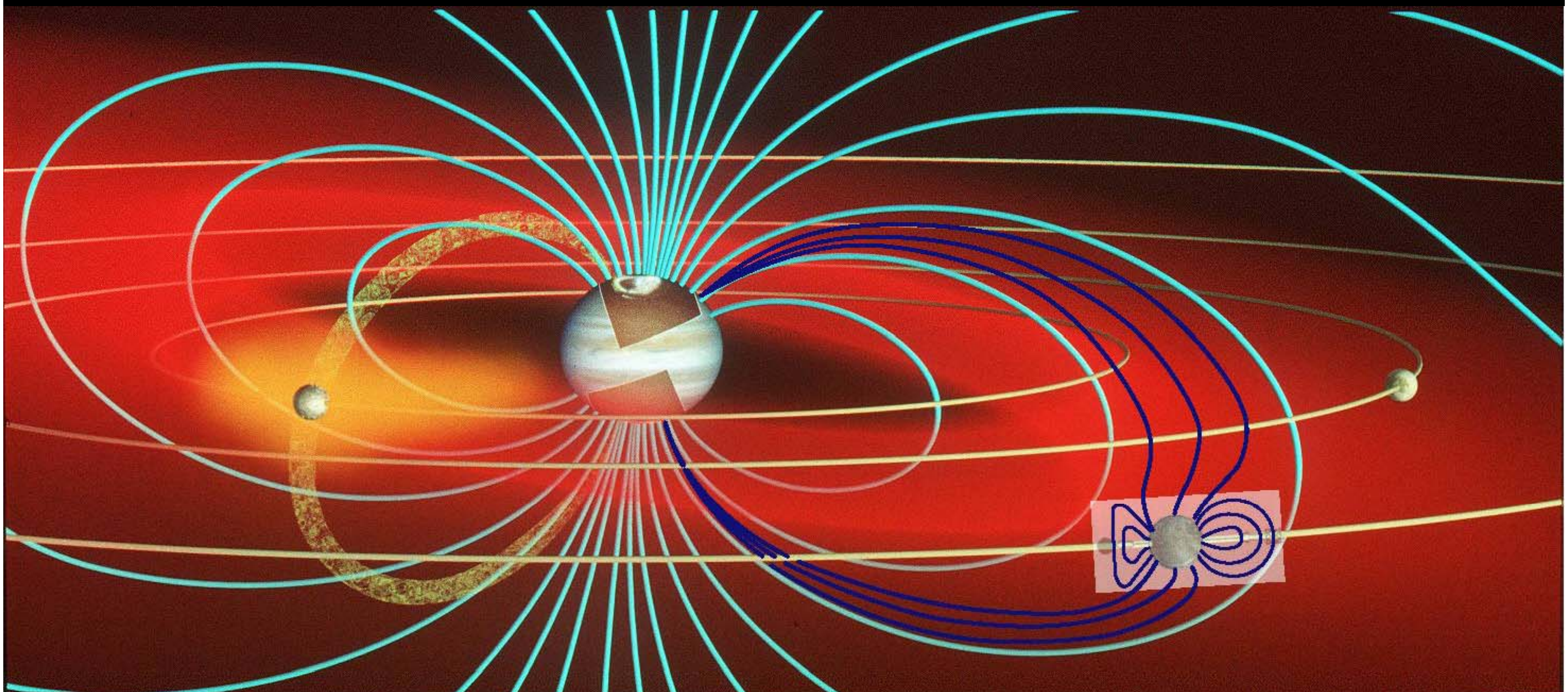


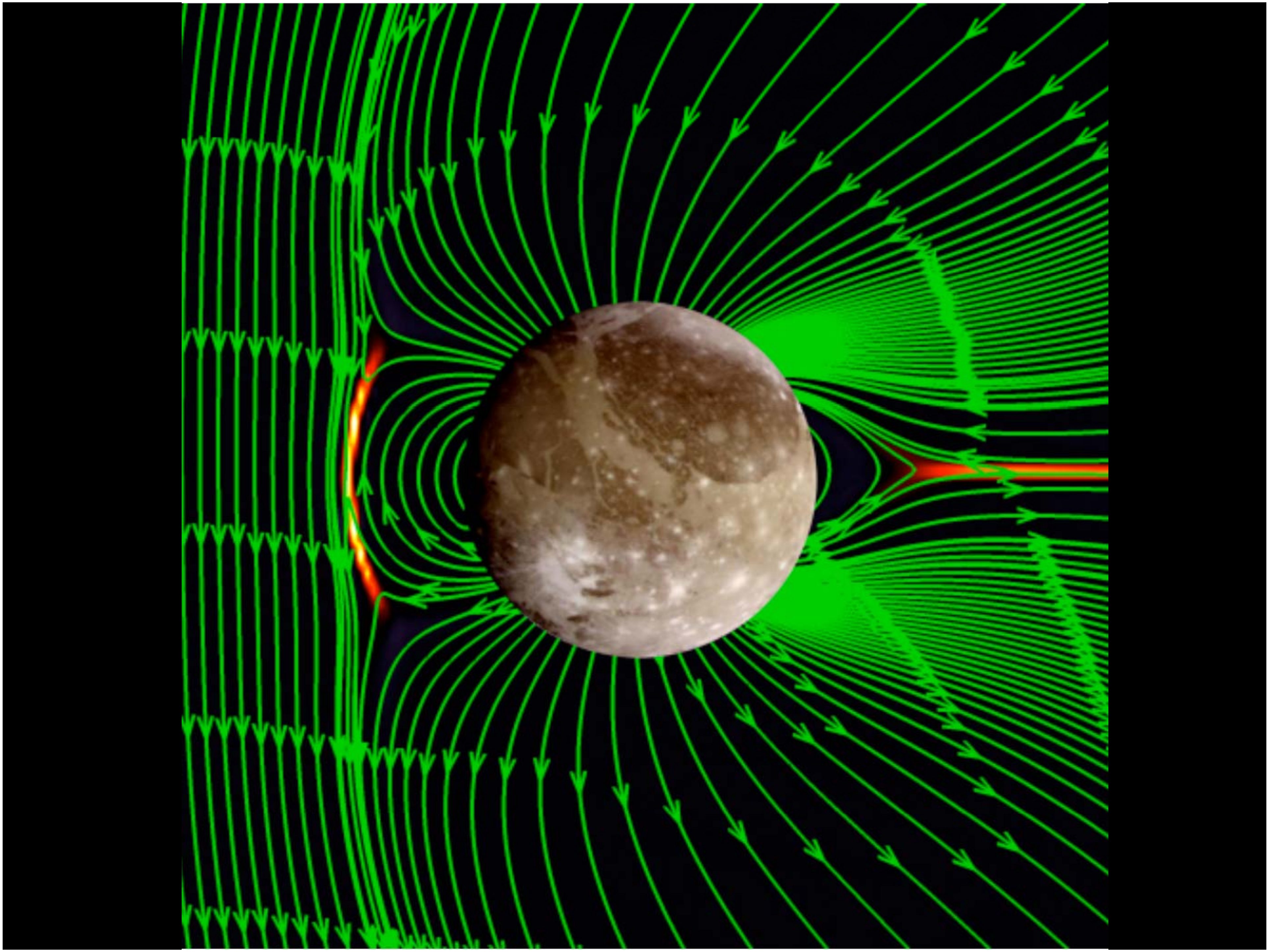
Atmosphere–Solar Nebula More Complicated than thought

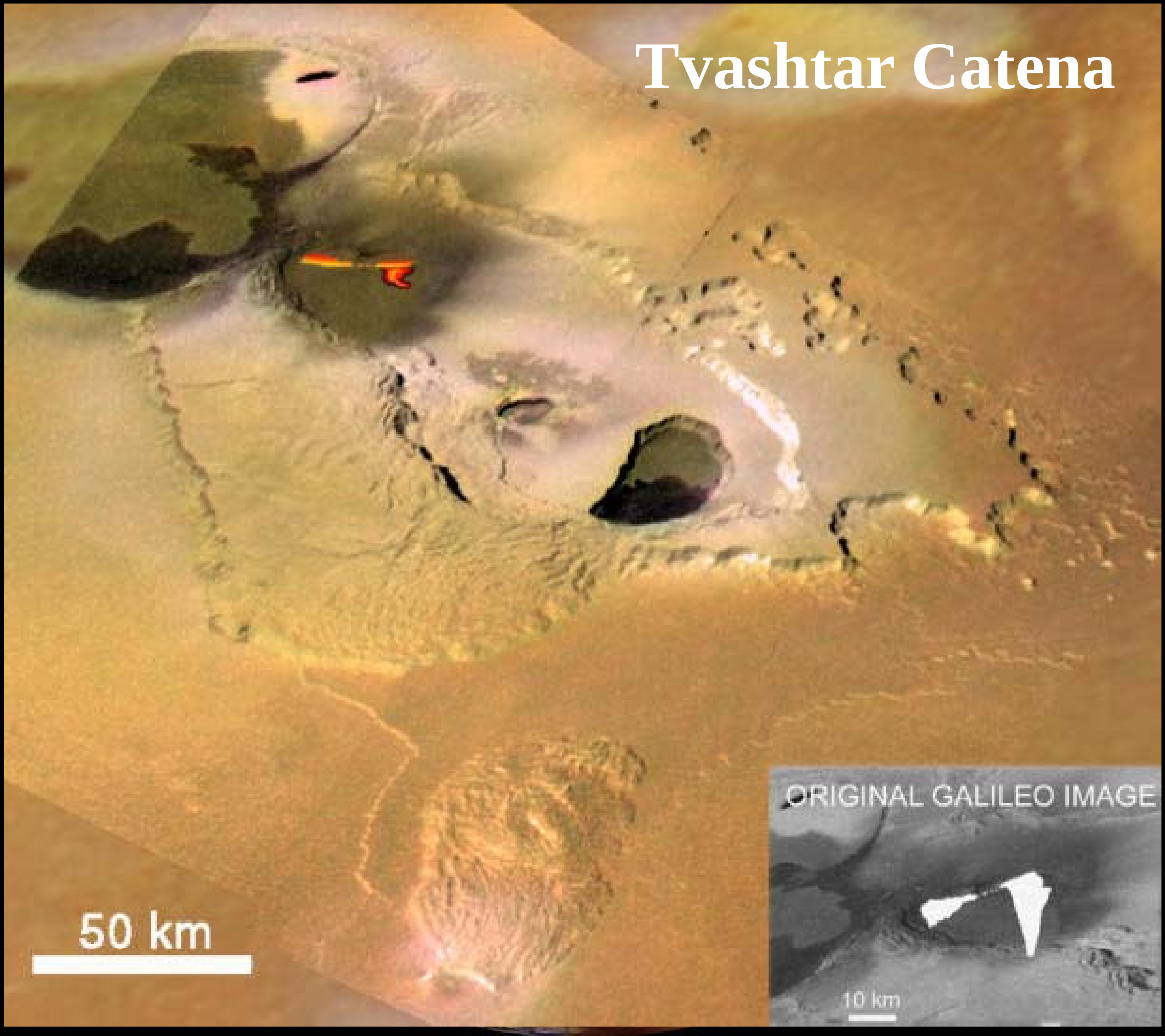
- Emphasis shifts from H/He and 'pure' sample of the original solar nebula to "how did depletions and enrichments occur?" – major Juno mission goal.
- Delivery of noble gases especially important – implies trapping in ices at much lower temperatures than thought to exist when Jupiter formed
- Currently driving new probe concepts for Saturn – recommended in current Decadal Survey as important New Frontiers target.

GALILEO SATELLITE RESULTS

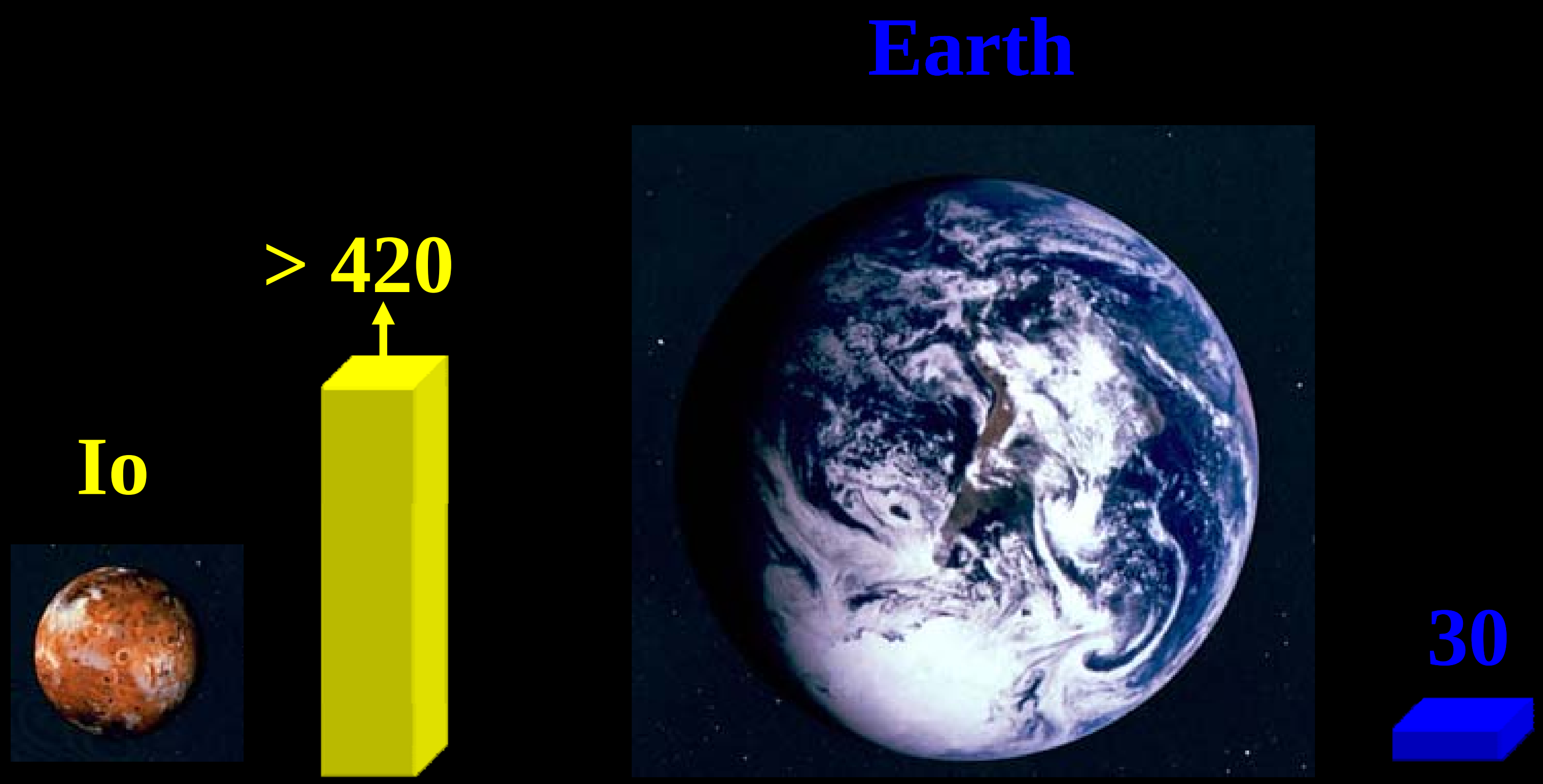
Ganymede: A Moon with Magnetism

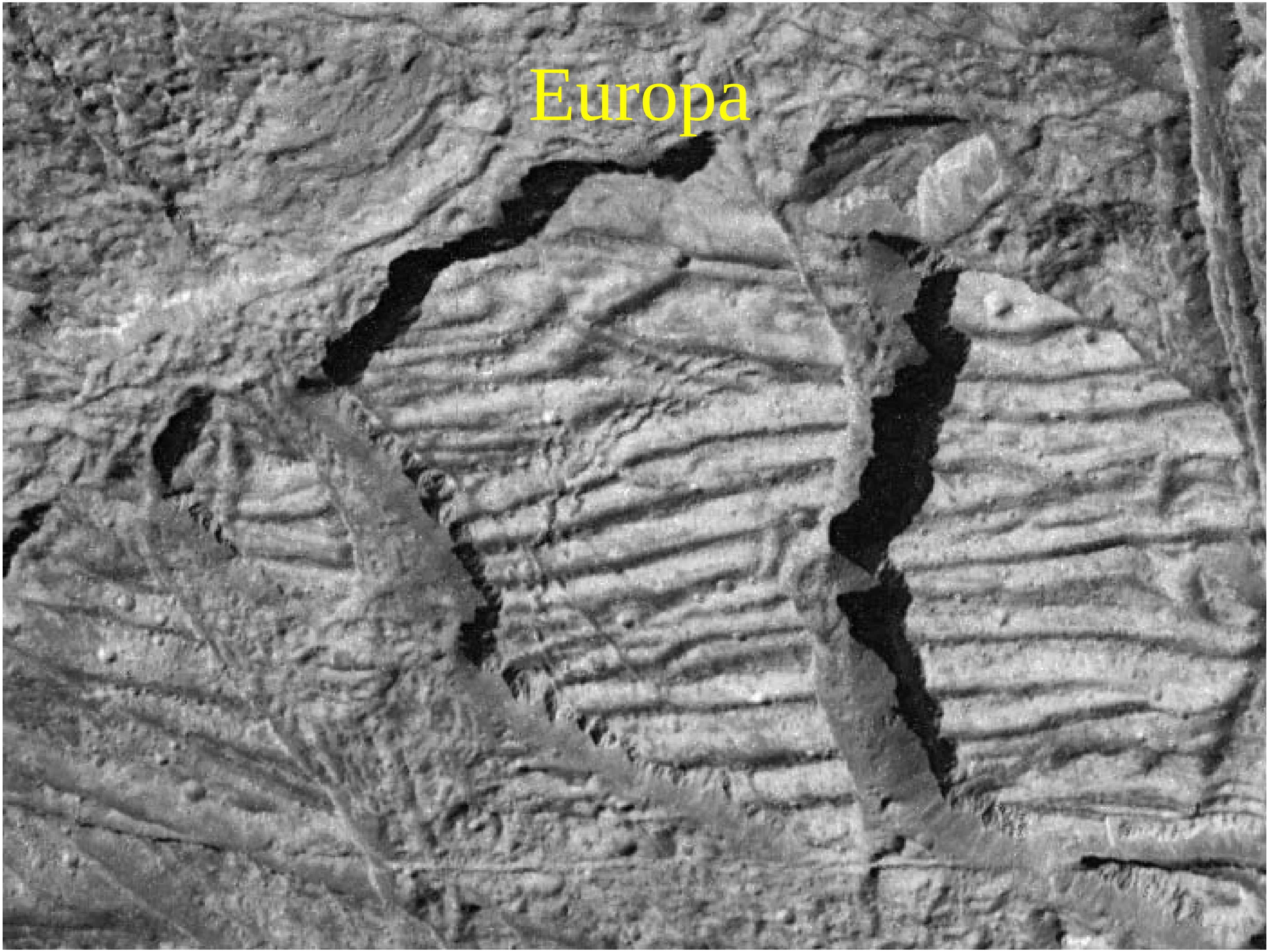





Tvashtar Catena
50 km
ORIGINAL GALILEO IMAGE
10 km

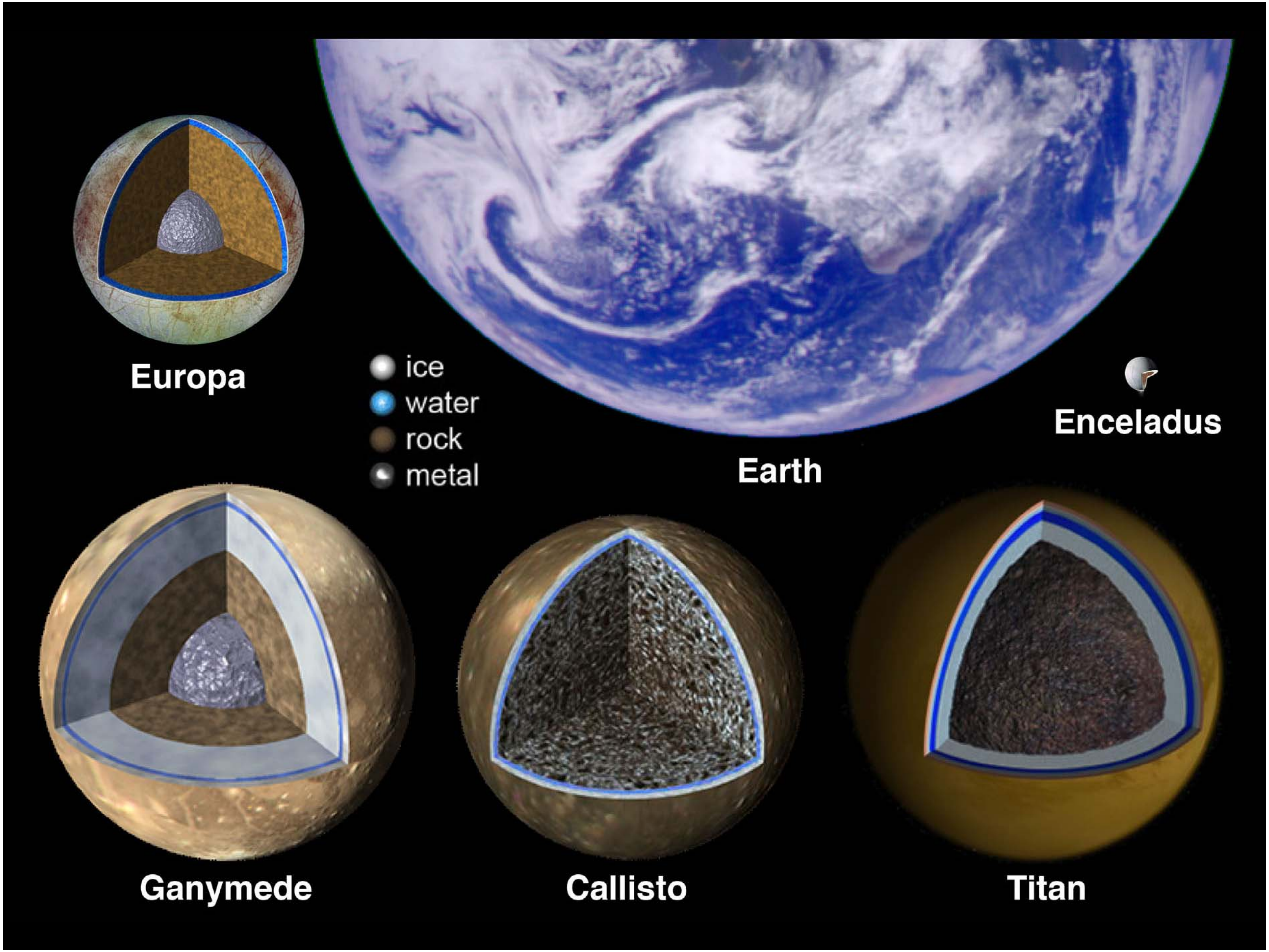
Magma Generation, km^3/yr

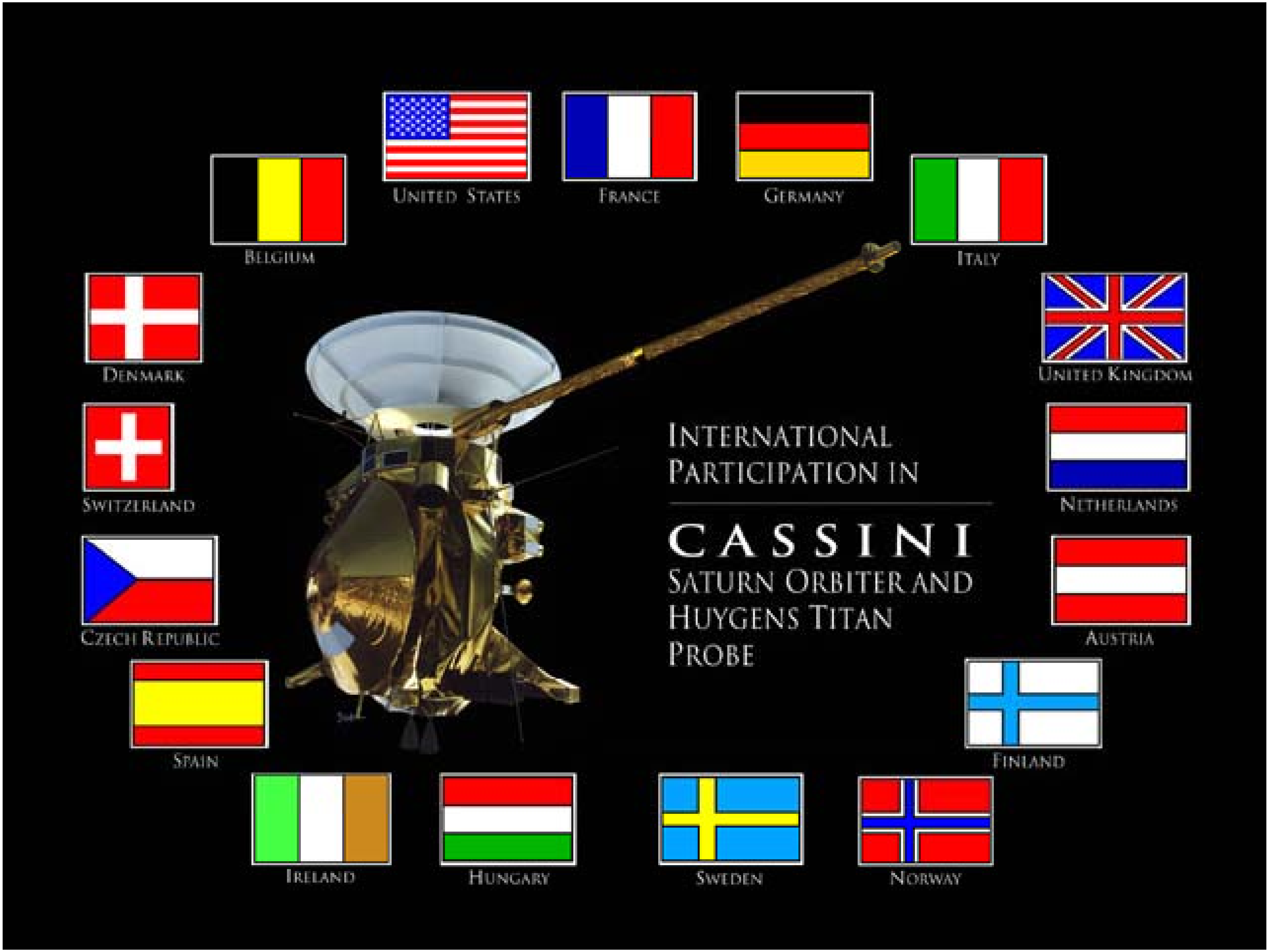


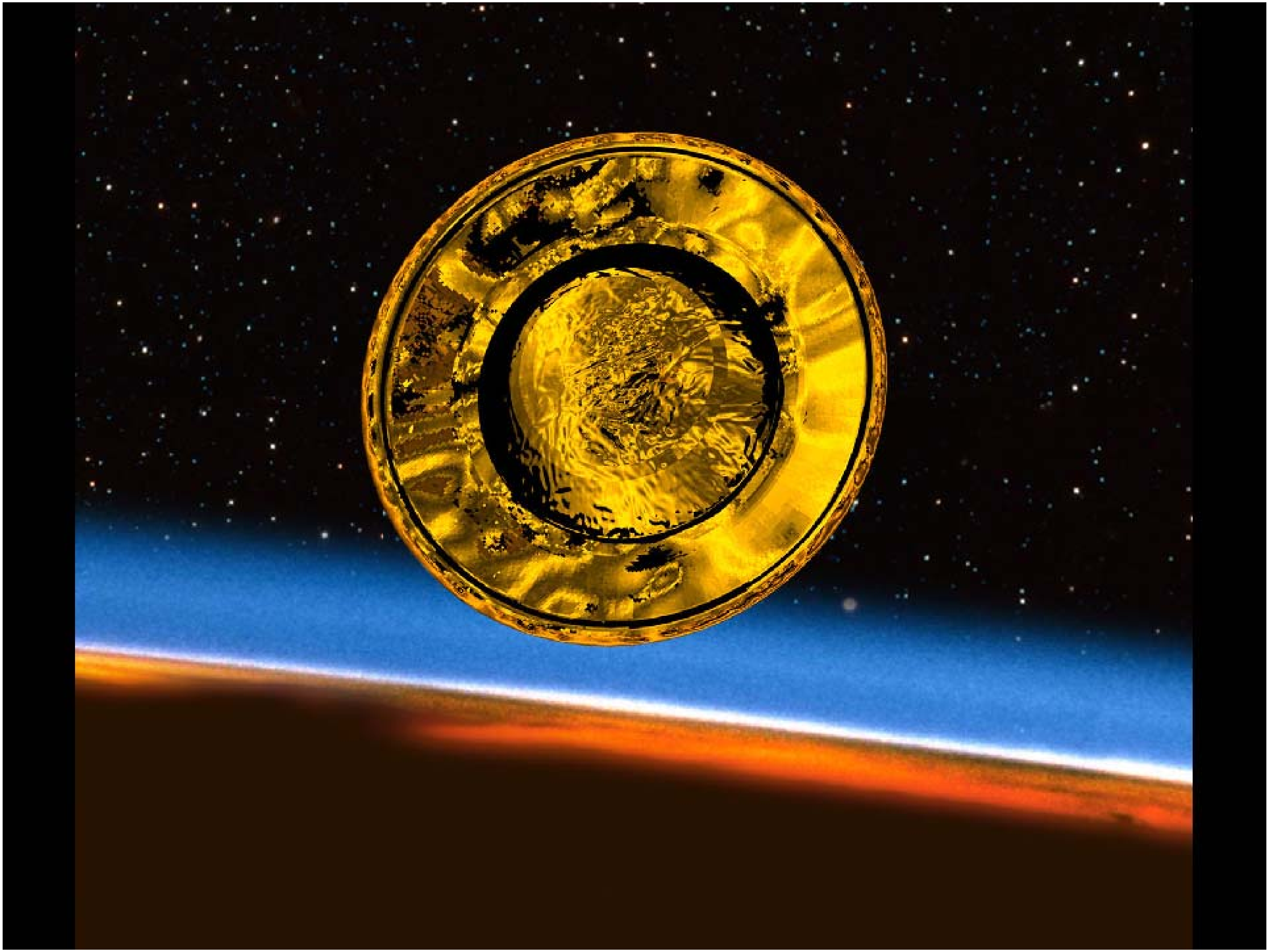

Europa

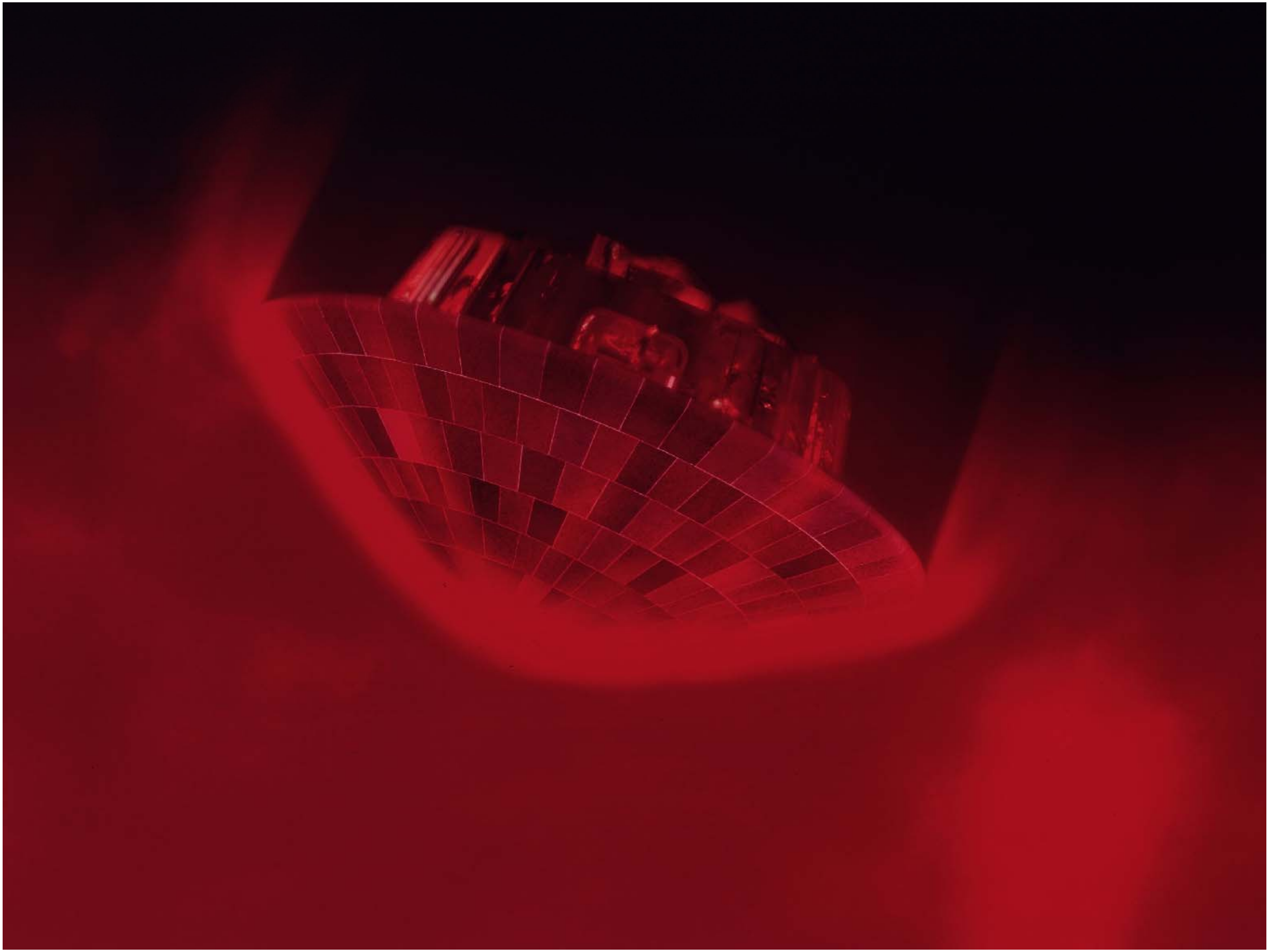
Magnetic Signatures of Oceans

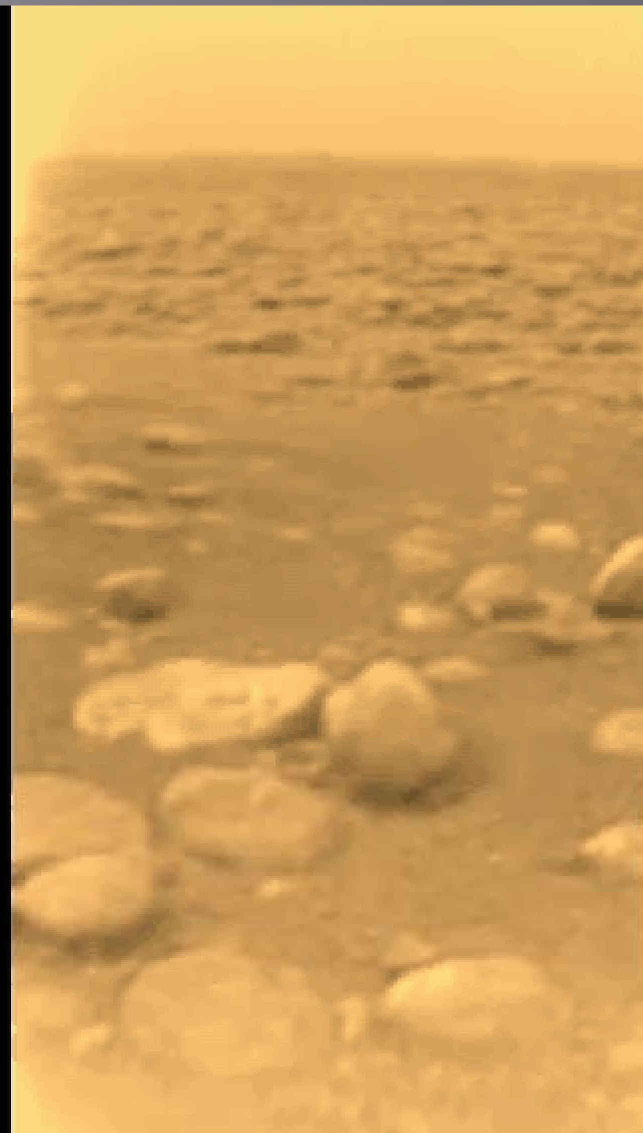
- Galileo's magnetometer experiment (M. Kivelson, PI) finds evidence that the icy moons – Europa, Ganymede, and Callisto - act like global scale electrically conducting spheres
- Required conductivity >> ice, rock, ionospheres, etc
- Salty seawater is ~ right

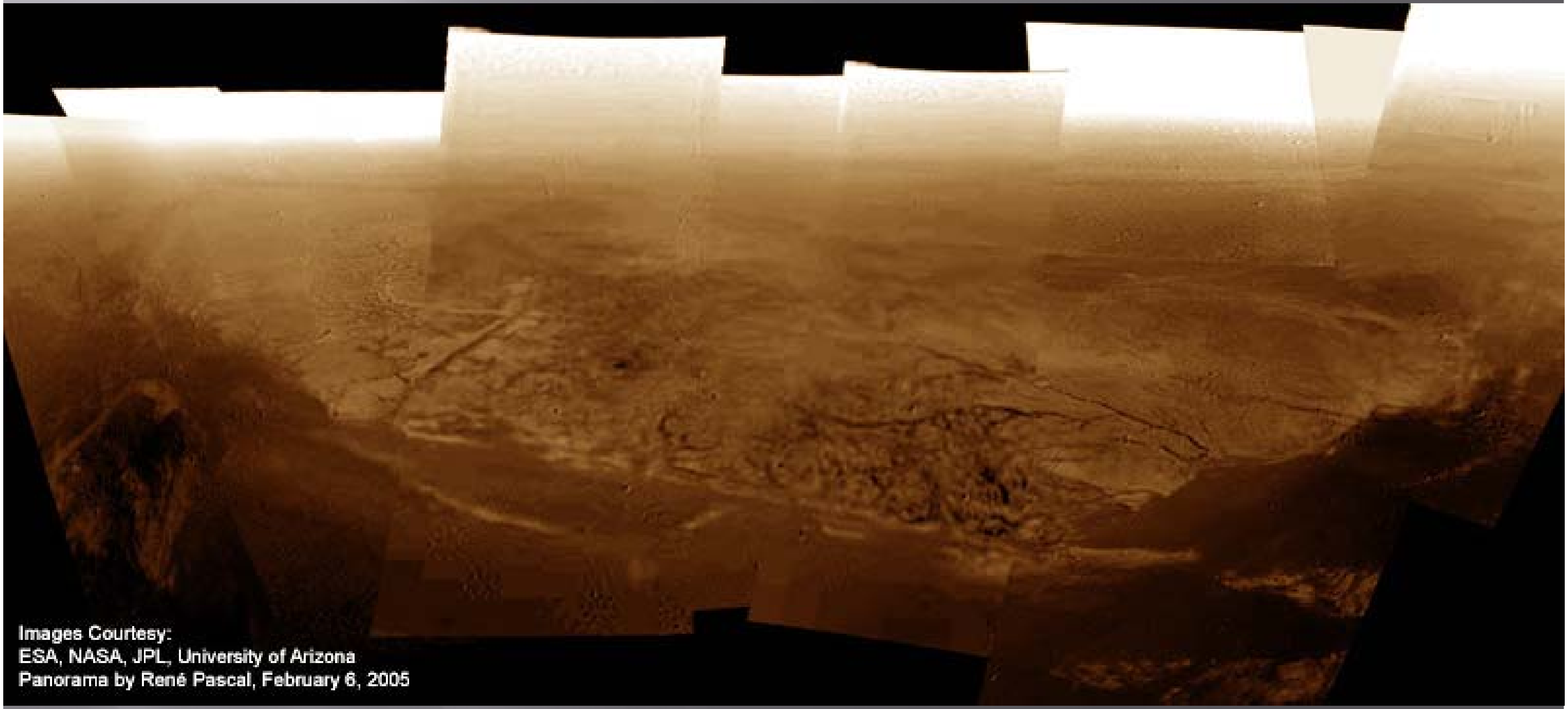

Europa
ice
water
rock
metal
Earth
Enceladus
Ganymede
Callisto
Titan

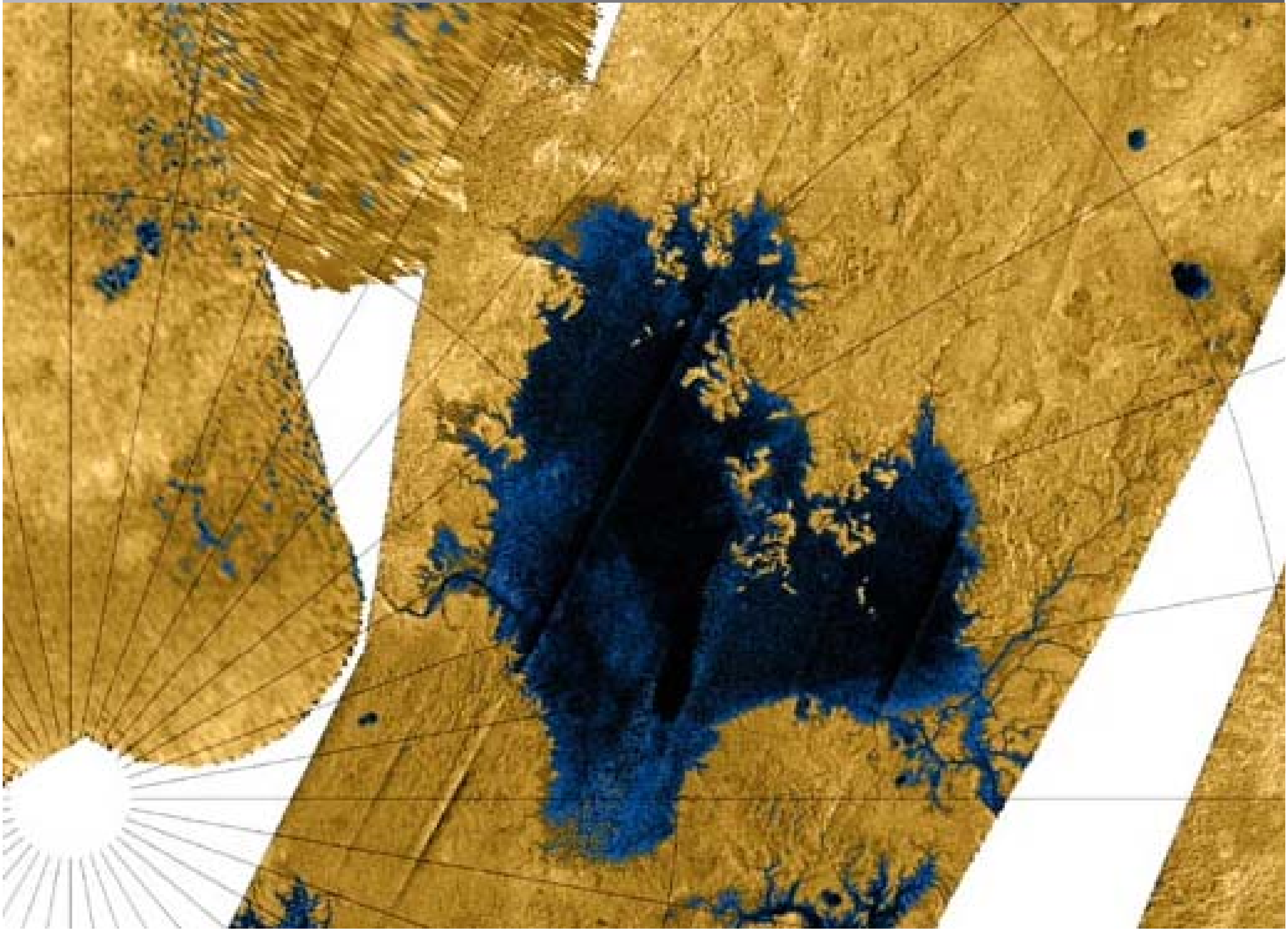

United States
France
Germany
Belgium
Italy
Denmark
United Kingdom
International Participation in
Cassini
Saturn Orbiter and Huygens Titan Probe
Switzerland
Netherlands
Czech Republic
Austria
Spain
Finland
Ireland
Hungary
Sweden
Norway



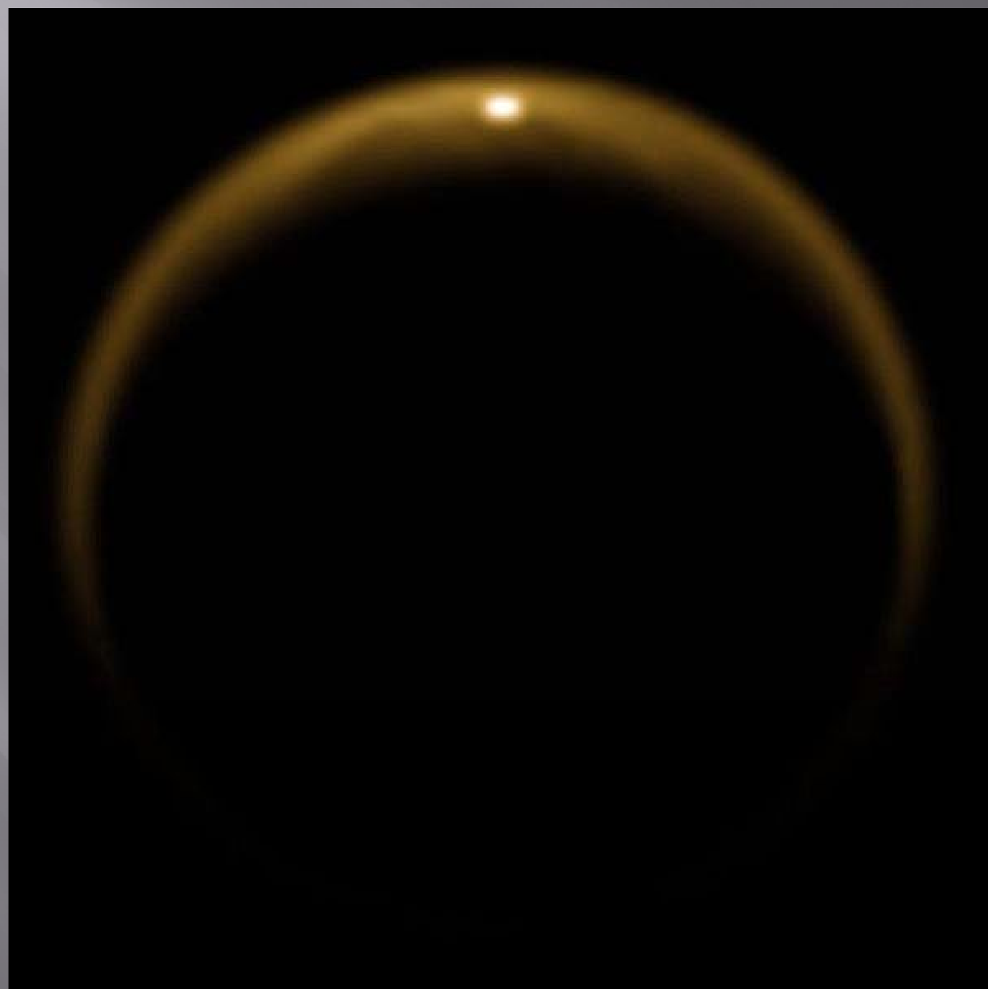




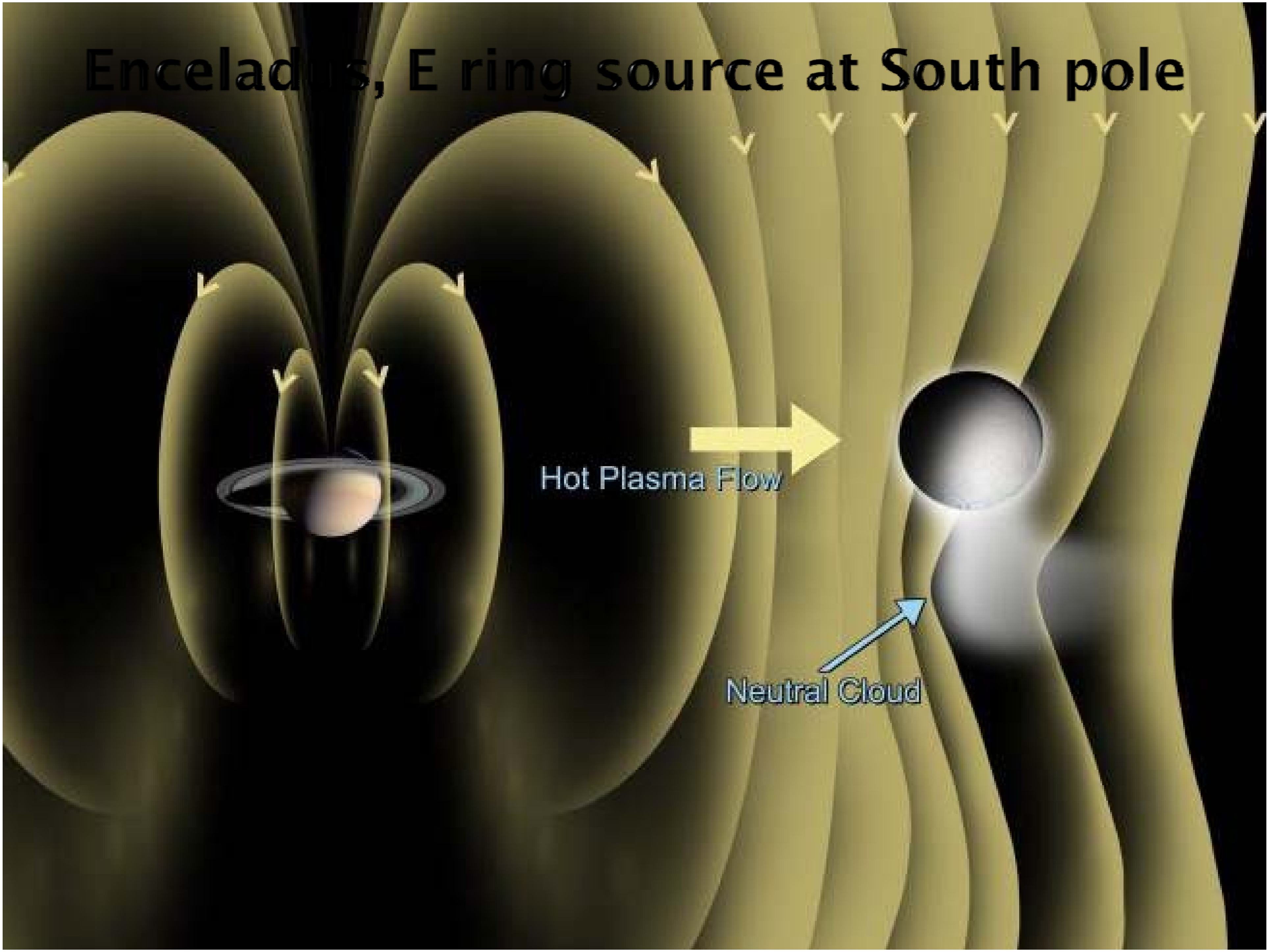

Images Courtesy:
ESA, NASA, JPL, University of Arizona
Panorama by René Pascal, February 6, 2005



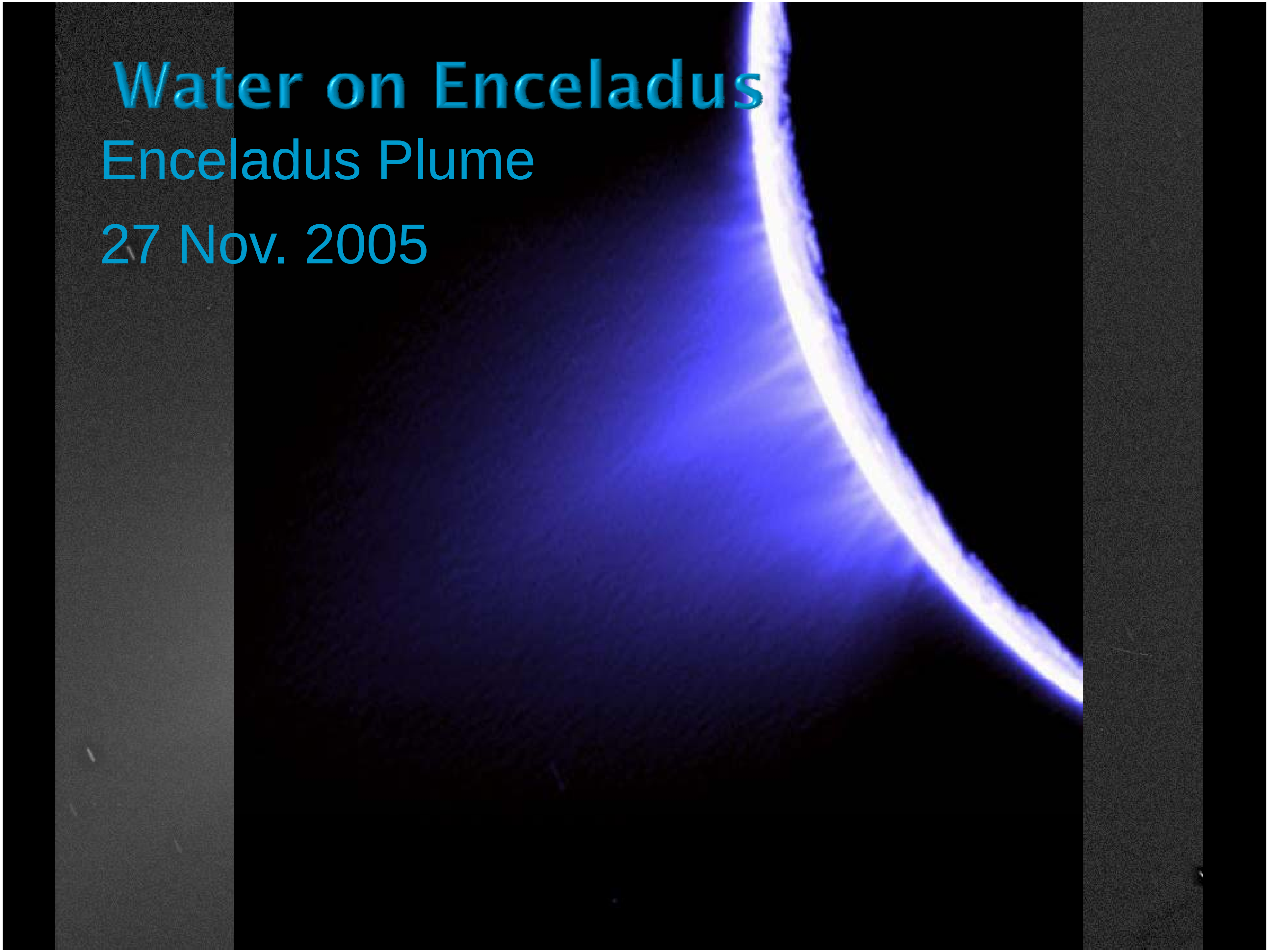
Specular Reflection from Titan's Lakes

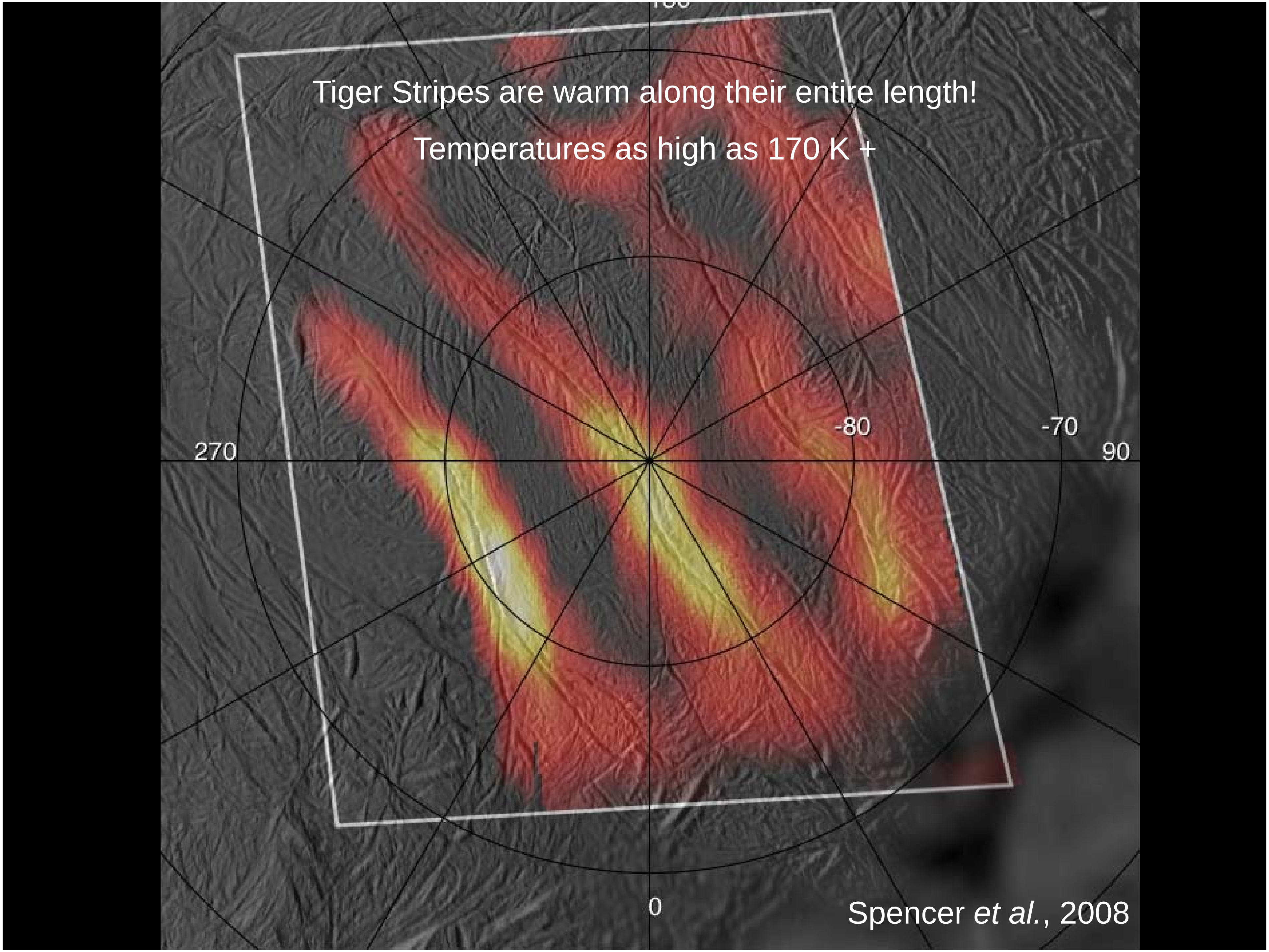


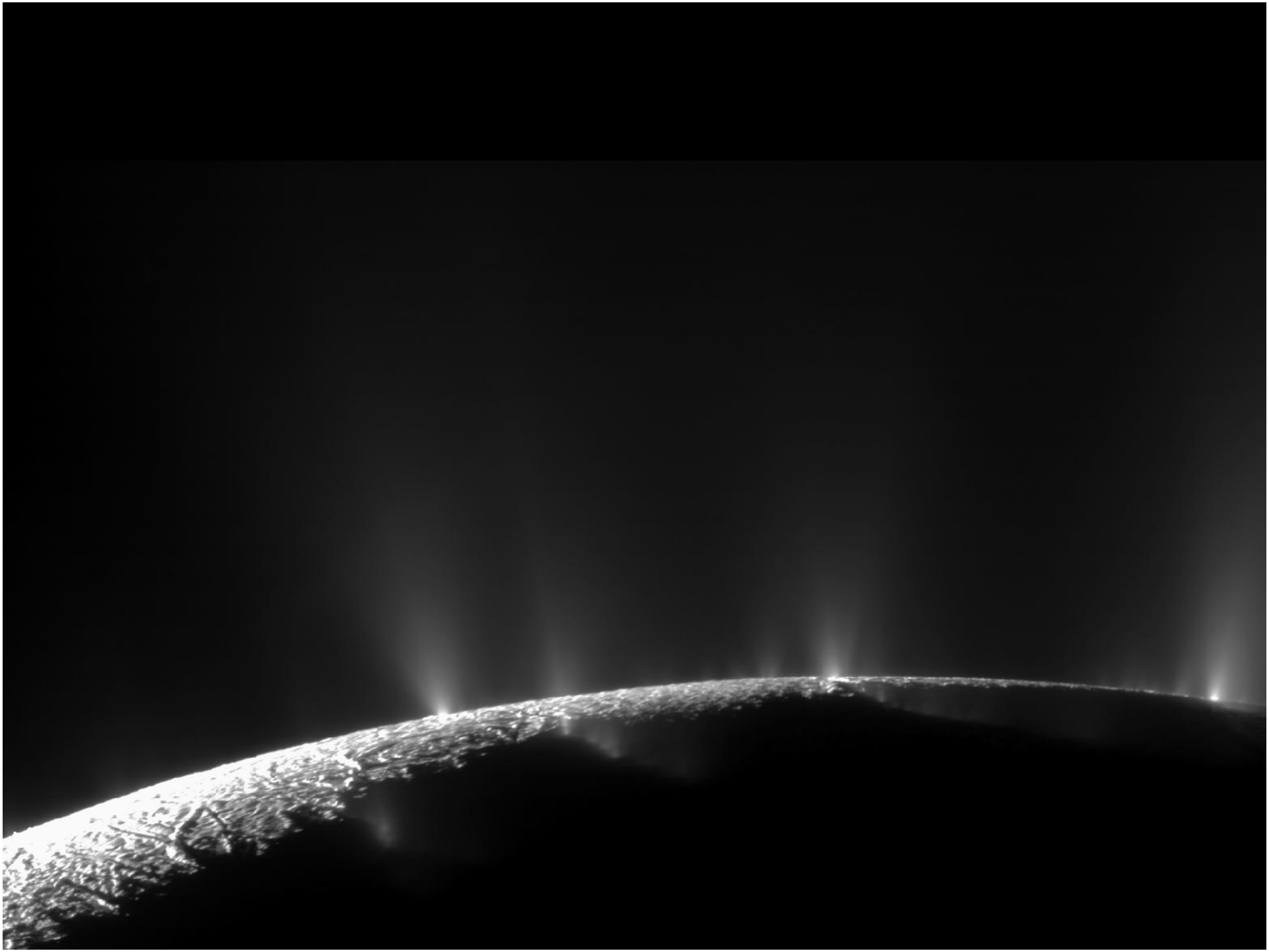
Enceladus, E ring source at South pole



Water on Enceladus

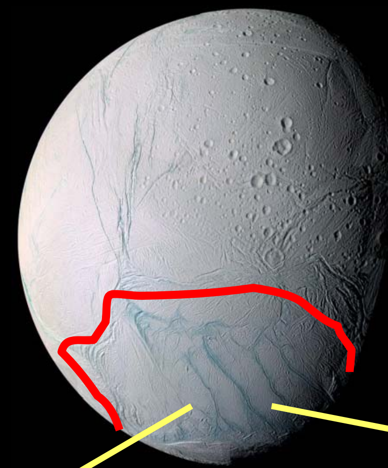



Tiger Stripes are warm along their entire length!
Temperatures as high as 170 K +
270
-80
-70
90
0
Spencer et al., 2008



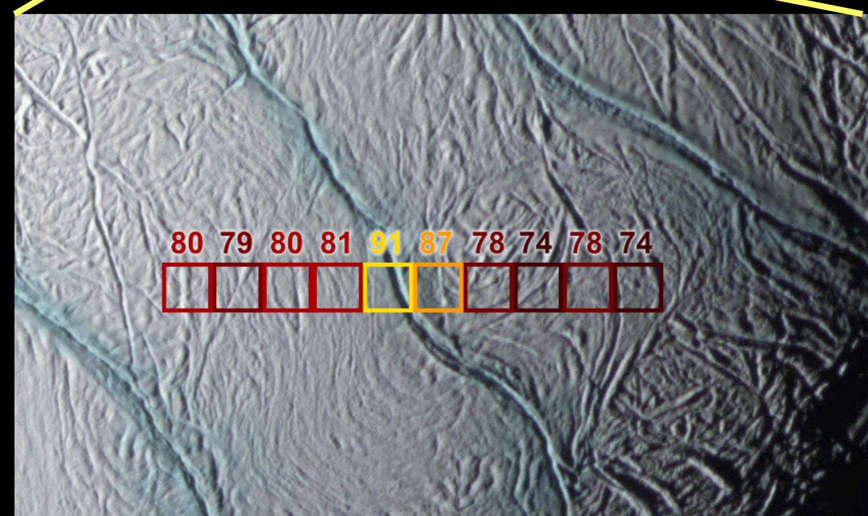
Planetary Heat Flow

Avg Earth
87 mW/m^2



Enceladus
South Polar Terrain
250 mW/m^2

Yellowstone
2500 mW/m^2



Tiger Stripes
13,000 mW/m^2

Scientists amazed …

Scientists surprised …

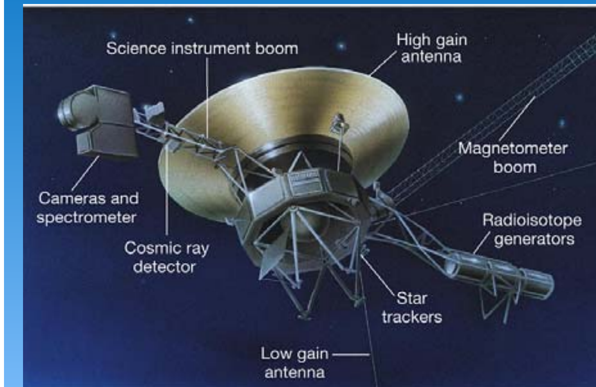
Textbooks rewritten!!

Unexpected result stuns scientists!

Well … Yes, Actually

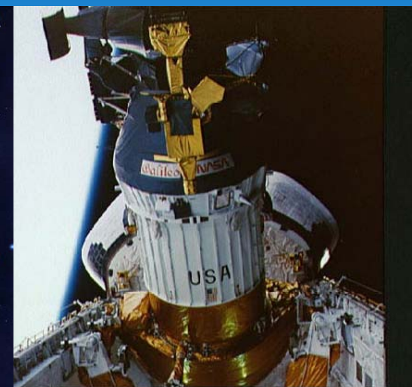

To be continued …..

Pioneer 10, 11
Launch 1971, 1972

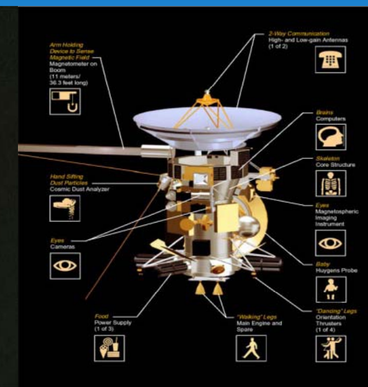


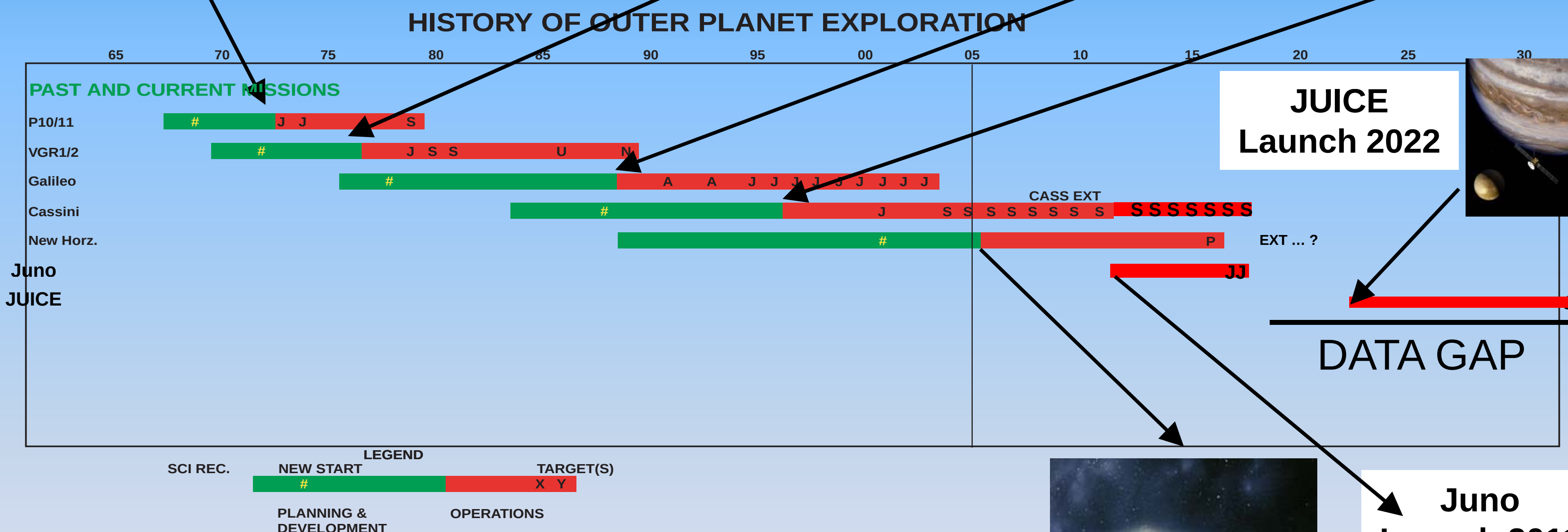
Voyager 1, 2
Launch 1977

Galileo
Launch 1989



Cassini
Launch 1997





OVER 30 YEARS OF CONTINUOUS DISCOVERY

New Horizons
Pluto/Kuiper Belt
Launch 2006

Juno
Launch 2011

[redacted]